N92-10871

IMPACTS AND ATMOSPHERIC EROSION ON THE EARLY EARTH; A. M. Vickery,
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Until recently, models for the origin and evolution of the atmospheres of terrestrial planets ignored the effects of accretionary impacts. In the 1970's, however, it was suggested that heating and/or vaporization of accreting carbonaceous-chondrite-type planetesimals could result in the release of their volatile components (1,2). Modeling of this process (e.g., 3,4) strongly suggests that substantial atmospheres/hydrospheres could develop this way. During most of the accretionary process, impact velocities generally differed little from the escape velocity of the growing proto-planet because most of the collisions were between bodies in nearly matching orbits. Toward the end of accretion, however, collisions were rarer but much more energetic, involving large planetesimals and higher impact velocities (5). It has been postulated that such impacts result in a net loss of atmosphere from a planet, and that the cumulative effect impacts during the period of heavy bombardment might have dramatically depleted the original atmospheres (6,7).

Walker (8) showed that shock heating and compression of the atmosphere by the projectile during entry can eject at most a few times the mass of the air traversed, which is generally a negligible fraction of the total atmospheric mass. The solid ejecta are also unable to eject more than a few times the mass of the air traversed by the projectile (9). The vapor plume produced by a sufficiently energetic impact is, however, capable of ejecting the entire atmospheric mass lying above a plane tangent to the planet at the point of impact (10). Models developed to study atmospheric erosion by impacts on Mars and the interaction of the vapor plume produced by the KT impactor on earth (11,12) are here applied to the case of the evolution of earth's atmosphere.

The simplest model involves estimating the minimum impact velocity and impactor mass required to eject the atmospheric mass above the tangent plane (M_{tp}) and concatenating this information with estimates of the impact flux. A model for vapor plume expansion (13) gives the mean expansion velocity as $[2(\varepsilon - \Delta H)]^{1/2}$, where ε is the initial internal energy of the vapor and ΔH is the vaporization energy. The internal energy of shocked material is $u^2/2$, where u is the particle velocity; for projectile and target of similar materials, the peak particle velocity is roughly half the impact velocity. By requiring that the mean expansion velocity exceed escape velocity, and using ΔH = 13 MJ/kg for silicats, the minimum impact velocity for atmospheric blow-off on earth is ~25 km/sec. Simple momentum balance suggests that the minimum impactor mass for blow-off is $m^* = M_{tp}$. The evolution of atmospheric mass with time is then given by

$$\frac{dM_{atm}}{dt} = -N_{cum}(m^*,t)4\pi R^2 M_{tp}$$

where $N_{cum}(m,t)$ is the cumulative number of impactors with masses greater than or equal to m (per unit area and per unit time) and R is the radius of the target planet. Using the approximation that $M_{tp} = H/2R$, where H is the scale height of the atmosphere, allows this equation to be integrated to find $M/M_0 = P/P_0$, that is, the ratio of the atmospheric mass (or pressure) at any time to its current value. Using this equation, P(-4.5 Gyr) $\cong 5 \times P_0$ for the earth (Figure 1). This contrasts sharply with the results of similar calculations for Mars, for which P(-4.5 Gyr) $\cong 100 \times P_0$. For both planets, however, the atmospheric loss rate is greatest during heavy bombardment and has been negligible since the end of heavy bombardment.

These calculations implicitly assume that the atmosphere is distributed homogeneously with respect to zenith angle, but the atmosphere is in reality concentrated near the horizon. More detailed numerical work, which takes this inhomogeneity into account, suggests that $m^* = 5$ to $10 \times M_{tp}$. This makes stmospheric erosion by impacts less efficient. Other factors tend to make atmospheric blow-off more efficient than these

models indicate. First, the latent heat of vaporization will be added back to the internal energy of the vapor plume as the material begins to condense. Second, when the acceleration due to pressure gradients with the plume becomes comparable to the acceleration due to gravity, the plume will descend below the tangent plane and so a single impact may blow off more than Mtp. Third, these calculations ignore partial blow-off, that is, loss of less than Mtp; because partial loss may occur for smaller but more numerous impactors, the net effect may be significant. Fourth, the effect of obliquity of impact has been neglected. Experiments suggest that oblique impacts produce more vapor than normal impacts with the same impactor mass and speed (14). Furthermore, this vapor has a velocity component downrange, which means that it is directed toward the highest atmospheric mass concentration. Oblique impacts may thus be much more efficient at ejecting atmosphere than normal impacts.

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